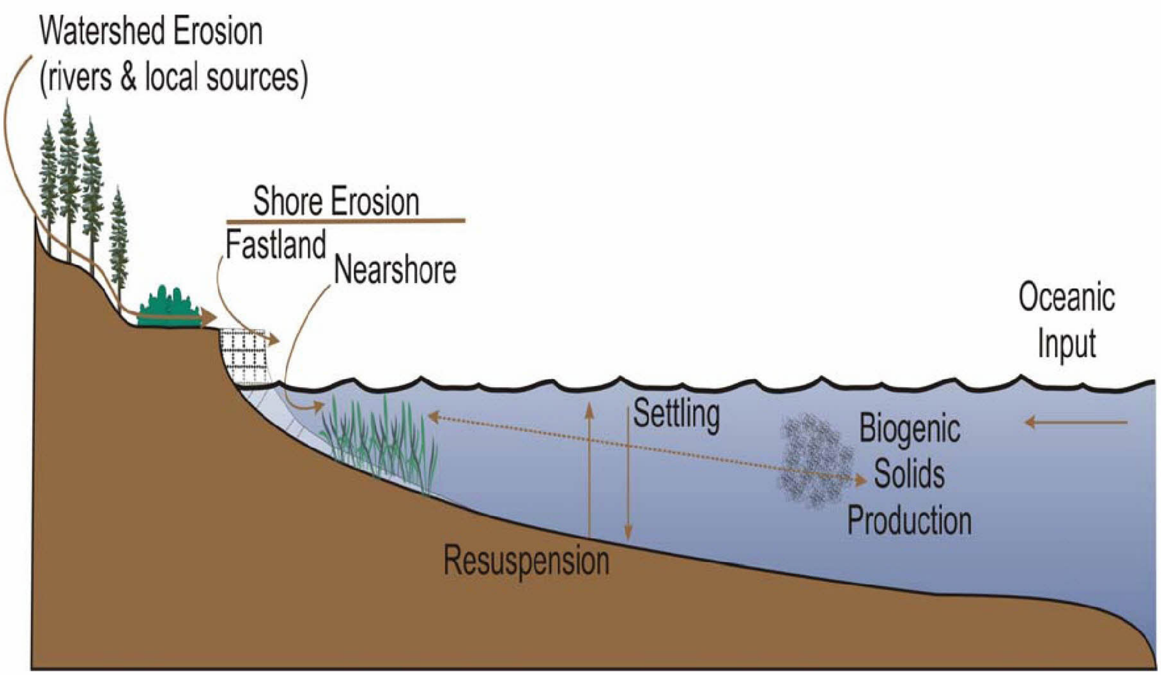
CBP-TRS-286-07

An Introduction to Sedimentsheds: Sediment and Its Relationship to Chesapeake Bay Water Clarity

Final Report



Chesapeake Bay Program
A Watershed Partnership

Chesapeake Bay Program Sediment Workgroup
May 2007

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List of Sediment Workgroup Members and Affiliation

Lead Editors

Lee Currey – Co-Chair, MD Department of the Environment
Jeffrey Halka - Co-Chair, MD Geological Survey
Keely Clifford - Coordinator, U.S. EPA, Chesapeake Bay Program Office

Workgroup Members (alphabetical)

Sally Bradley	Fellow, Chesapeake Research Consortium
Owen Bricker	US Geological Survey
Grace S. Brush	Johns Hopkins University
Keely Clifford*	Environmental Protection Agency
Thomas M Cronin	US Geological Survey
Lee Currey*	MD Department of the Environment
Allen Gellis*	US Geological Survey
Amy Guise	US Army Corps of Engineers
Jeffrey Halka*	MD Geological Survey
Julie Herman*	VA Institute of Marine Science
Timothy Karikari	DC Department of Health
Jean Kapusnick	US Army Corps of Engineers
Mike Langland*	US Geological Survey
Doug Levin	National Oceanic and Atmospheric Administration
Lewis Linker*	Environmental Protection Agency
Kevin McGonigal	Susquehanna River Basin Commission
Sara Parr	Chesapeake Research Consortium
Kenn Pattison	PA Department of Environmental Protection
Scott Phillips	US Geological Survey
Larry Sanford	University of MD Center for Environmental Science
Gary Shenk	Environmental Protection Agency
Sean Smith	MD Department of Natural Resources
Chris Spaur*	US Army Corps of Engineers
Steve Stewart	Baltimore County Department of Environmental Protection & Resource Management
Debra Willard	US Geological Survey
David Wilson	Maryland Eastern Shore RC&D Council

*Indicates contributing author to report.

Acknowledgments

This report relied heavily on contributions from discussions during Sediment Workgroup meetings, cited literature, contributed unpublished work and the existing compilation report, developed through the Sediment Workgroup, and titled "A Summary Report of Sediment Processes in Chesapeake Bay and Watershed" (Langland and Cronin, 2003). The authors wish to express their gratitude to workgroup members who did not contribute to "authorship" explicitly as their comments during meetings significantly contributed to conclusions outlined in this report. Finally, a special acknowledgement to Dr. Larry Sanford of the University of Maryland for his guidance and help in developing the STAC sedimentshed workshop, Thomas Simpson of the University of Maryland, and Rich Batik and Kelly Shenk of the U.S. EPA, Chesapeake Bay Program Office for providing clarification of Sediment Workgroup goals and guidance on how to achieve them.

1 Introduction and Purpose

Recent development and adoption of water clarity criteria and their tidal water clarity standards regulations for protection in the Shallow Water Bay Grass Designated Use (SAVgrow zone) areas of the Bay have placed a significant emphasis on the effect of sediment loads on Bay water clarity (USEPA 2003a, 2003b). Furthermore, previous modeling results indicated that sediment reductions from the watershed alone and nutrient reductions called for in the Tributary Strategies would not be sufficient to meet the new state water clarity-submerged aquatic vegetation (SAV) acreage water quality standards (USEPA 2003c; Cerco et al., 2002, Cerco et al. 2004). Success in achieving the states' water clarity-SAV acreage water quality standards will require recognition of the many factors affecting water clarity and their origin within the Bay and watershed.

The Chesapeake Bay Program's Sediment workgroup was assigned the task of developing sedimentsheds. The purpose of the sedimentsheds is that they would be applied to determine the source of sediment that is contributing to water clarity violations in a SAV grow zone with the intent of using these results in the 2010 sediment reallocation process. The concept is expected to be similar to that of the previous determination of the airsheds which were used to determine the spatial extent of atmospheric nutrient sources affecting critical regions of the Bay.

The first step in the sedimentshed development process was to gain a collective understanding of what a sedimentshed represents. The Sediment Workgroup defined a sedimentshed as the area, including watershed, near-shore and sub-aqueous, that contributes the sediment that directly influences water clarity in SAV grow zones. Discussions also identified complicating issues in developing a sedimentshed, such as spatial scale and the timing of sediment transport, which includes the delivery of legacy sediment from the watershed and subsequent resuspension of sediment once in the tidal waters of the Bay. With consideration of these issues, the workgroup went to the next step, which was to define a process for delineating a sedimentshed.

It was suggested from comments during the workgroup meetings that the delineation of a sedimentshed for a specific SAV grow zone would require either monitoring data directed at identifying the source of the sediment (i.e. watershed, shore erosion, resuspension, etc.) or a mechanistic spatially and temporally varying model that accounts for the predominant physical processes in Bay wide sediment transport. Currently there is not a Bay wide sediment source tracking monitoring program, however, there is a joint modeling effort by the Chesapeake Bay scientific community using the best science and information available to simulate the predominant sediment transport processes in the Bay watershed and the Bay tidal waters and the subsequent effect of suspended sediment on the SAV community. However, this refined water quality model is not expected to be completed until the summer of 2007 (for testing runs only). As a result, it was determined that sedimentsheds probably could not be delineated until the model is completed, however, the workgroup could begin setting the foundation for sedimentshed development.

Setting the foundation for sedimentshed development resulted in asking three simple questions.

- First, what sources of sediment would potentially be present during a critical growing period in an SAV grow zone? What are the primary transport mechanisms for the sources?

- Second, what is the appropriate scale for delineating a sedimentshed?
- Third, considering limited resources, where should we prioritize our efforts for delineating sedimentsheds?

This report presents preliminary answers to these three questions.

Section two of this report provides a brief review of the process used in determining the existing sediment allocations based on the previous Chesapeake Bay Program model version 4.3, the sediment source categories included and the scale at which the allocations were defined. Section three presents the current Bay water quality segmentation used to determine if an area of the Bay is deficient in SAV acres, which begins to address a potential scale based on the state's regulatory listing of impaired waters. Section four provides a narrative of the predominant sediment sources expected to impact an SAV grow zone with recognition of significant sediment transport processes. Section five presents an exploratory analysis of Bay wide water quality monitoring data with the purpose of prioritizing areas with poor water clarity and high inorganic solids (sediment) in the water column. Section six address future directions and major conclusions from the Scientific and Technical Advisory Committee (STAC) Sedimentshed Workshop held January 30-31, 2007.

2 History of Sediment Allocations - The 2003 Sediment Cap Load Allocations

Sediments suspended in the water column reduce the amount of light available to support healthy and extensive SAV communities. The relative contribution of suspended sediment and algae that cause poor light conditions varies with location in the Bay tidal waters (U.S. EPA, 2003a). The Chesapeake Bay Program partners agreed that a primary reason for reducing sediment loads to the Bay tidal waters is to assist in improving water clarity with the ultimate goal of restoring SAV. "As a result, the cap load allocations for sediments are linked to the recommended water quality criteria and the new SAV restoration goals and recognize that sediment load reductions are essential to SAV restoration" (U.S. EPA, 2003c). The jurisdictions also agreed that nutrient load reductions are critical for restoring SAV as well as improving oxygen levels (Murphy, Jr., 2003).

To support the sediment cap load allocations, it became clear that updated SAV restoration goals were needed (U.S. EPA, 2003a). The partners explored various methodologies for developing a Bay wide SAV restoration goal using the available historical record. The methodology selected used aerial photography from the 1930s to the present to identify the best year of record (in terms of SAV acres) for each Chesapeake Bay Program segment. The acreage determined to be the best year of record was designated as the SAV acreage goal for that segment. In aggregating all of the single best year results for each segment, a Bay wide SAV acreage restoration goal of 185,000 acres was established (U.S. EPA, 2003c).

Unlike nutrients, where loads from virtually the entire Chesapeake watershed affect mainstem Bay water quality, impacts from sediment loads are thought to be more localized (U.S. EPA, 2003c). For this reason, local, segment-specific SAV acreage goals have been established and the sediment cap load allocations are targeted towards achieving those restoration goals.

In 2003 the Chesapeake Bay Program partners agreed for the first time to combine reductions in watershed sediment inputs with nutrient reductions to the Chesapeake. <u>The partners agreed to watershed sediment reductions from the current estimated 5.83 million tons per year to the sediment cap load of 4.15 million tons.</u> These sediment reduction goals, adopted as loading caps allocated by major tributary basins by jurisdiction, are to help improve water clarity and assist in the restoration of 185,000 acres of SAV.

The partners recognize that the current understanding of sediment sources and their impact on the Chesapeake Bay is incomplete. Currently, understanding of watershed sediments that are carried into local waterways through runoff and stream bank erosion is still basic. Knowledge about coastal sediments that enter the Bay and its tidal rivers directly through shore erosion, near-shore erosion or shallow water resuspension is even more limited. Finally, the transport and deposition of fine-grained sediments once in the estuary is poorly understood. Consequently, the sediment cap load allocations are currently focused on watershed sediment cap loads by major basin and jurisdiction, e.g., a Pennsylvania Susquehanna watershed sediment cap load allocation of 0.79 millions of tons/year (U.S. EPA, 2003c). Major monitoring, research and modeling projects are underway to improve our understanding of these complex sediment processes.

Better understanding will inform management decisions and help direct actions needed to achieve the water clarity standard, and assist with a sediment re-allocation process expected in 2008 – 2010.

Most watershed best management practices, which reduce nonpoint sources of phosphorus, also will reduce sediment runoff. Consequently, the partners agreed to phosphorus-equivalent sediment cap load allocations that were based on sediment load reductions expected from land-based non-point source phosphorous controls necessary to achieve the phosphorous allocation (U.S. EPA, 2003c). To meet the 185,000 acre SAV restoration goal, Maryland, Virginia, Delaware and Washington, D.C. adopted water clarity standards into their water quality regulations.

Based on Watershed Model version 4.3 outputs, sediment and nutrient reductions from the watershed alone are estimated to be insufficient to achieve the water clarity necessary for the 185,000 acre SAV restoration goal (Cerco et al., 2002; Cerco et al., 2004; U.S. EPA, 2003c). Given the uncertainties surrounding tidal erosion, the partners did not consider allocating caps for sediment loads from tidal erosion or shallow water sediment resuspension. Management actions to control sediment from these sources may include, but are not limited to SAV planting, offshore breakwaters, shore erosion controls, living shorelines and structures, beach nourishment, and establishment of fisheries and filter feeders such as oysters and menhaden (Cerco and Noel 2005a: Cerco and Noel 2005b; Deksenieks et al., 1993; Durbin and Durbin, 1998; Kemp et al., 1994; Kemp et al., 2005; Newell et al., 2002; Newell et al., 2005).

3 Sedimentsheds and Setting the Geographic Scale

The first step in defining a sedimentshed is determining the scale of the SAV grow zone as this will define the spatial extent of water column sediment sources that must be identified. Recall that a sedimentshed is defined as the area that contributes the sediment that directly influences water clarity in near-shore SAV growing zones. After several discussions within the Sediment Workgroup, there has been no consistent agreement on a scale. The reason is that if the sedimentshed is to be used to assist in both sediment allocations and sediment management/implementation activities, these could be two very different scales, the first being a larger area and the second focusing in on specific management actions for a shoreline reach.

An argument can be made that an appropriate management scale for defining a SAV grow zone for sedimentshed delineation would be the Chesapeake Bay water quality segmentation scheme (see Figure 3-1). The primary reason for selecting this is that the Bay states have adopted this segmentation into their water quality standards and subsequent listing of impaired water bodies. It is therefore likely, that at this scale, states will be required to determine Total Maximum Daily Loads (TMDL) for segments that do not meet water quality criteria by the year 2010. Furthermore, one of EPA's TMDL requirements is that a TMDL must include source allocation and a sedimentshed delineated at this scale would identify the sources impacting water clarity. However, there also may be consideration, based on a scientific and/or regulatory basis, in grouping or aggregating multiple water quality segments (i.e. major tributary).

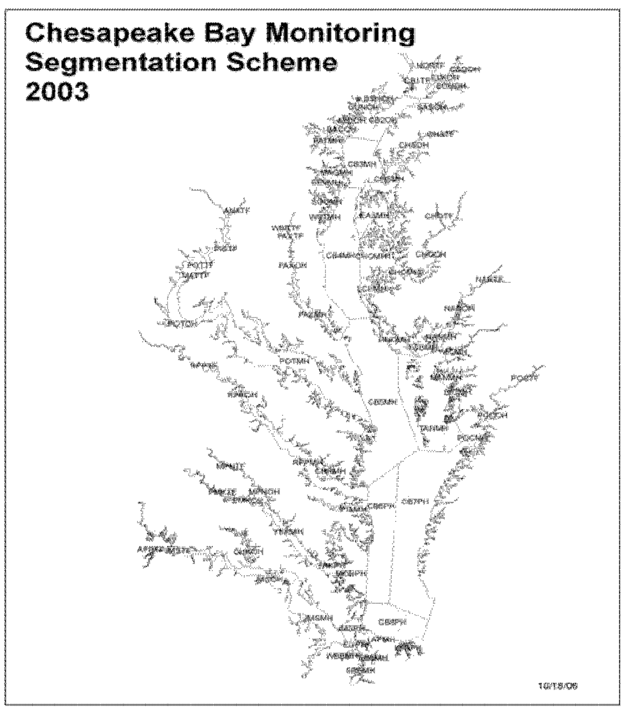

Figure 3-1. Chesapeake Bay Water Quality Segmentation (CBPO, 2003)

While consideration should be given to balancing the scale of regulatory requirements related to states 303(d) listing process and the scale at which implementation activities are designed, it is also important to recognize that the SAV growing area is a narrow ribbon along the shoreline. Figure 3-2 depicts the actual SAV growing areas, which extends out to a two meter water depth, compared to the Bay itself. We need to identify the origin of suspended sediment within a narrow ribbon extending out to two meters depth adjacent to the shoreline.

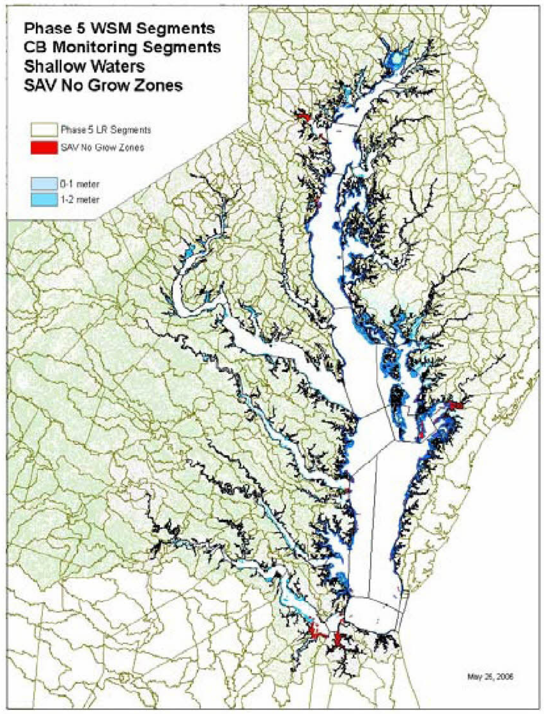

Figure 3-2. Chesapeake Bay SAV growing areas and no grow zones (CBPO, 2006)

4 Sediment Source and Sinks

4.1 Background

The second step in defining a sedimentshed, once the scale of the SAV area has been determined, is to list the sources of sediment that are likely contributors to the area and estimate the relative contribution of these sources. To illustrate the sediment sources and transport processes contributing to nearshore water column suspended sediment, a sediment transport in nearshore region conceptual model is presented in Figure 4-1. This figure identifies external sources of sediment as watershed erosion, fastland erosion and oceanic input. Internal sources of sediment include nearshore erosion and biogenic production. Horizontal and vertical transport processes, including settling and resuspension, result in a mixing of the source components throughout the Bay. Various regions of the Bay will be more or less impacted by these sources, transport processes and sinks. For example, the oceanic input source diminishes with distance from the Bay mouth, and the shore erosion component, both fastland and nearshore, will vary with shoreline orientation, composition, and degree of protection.

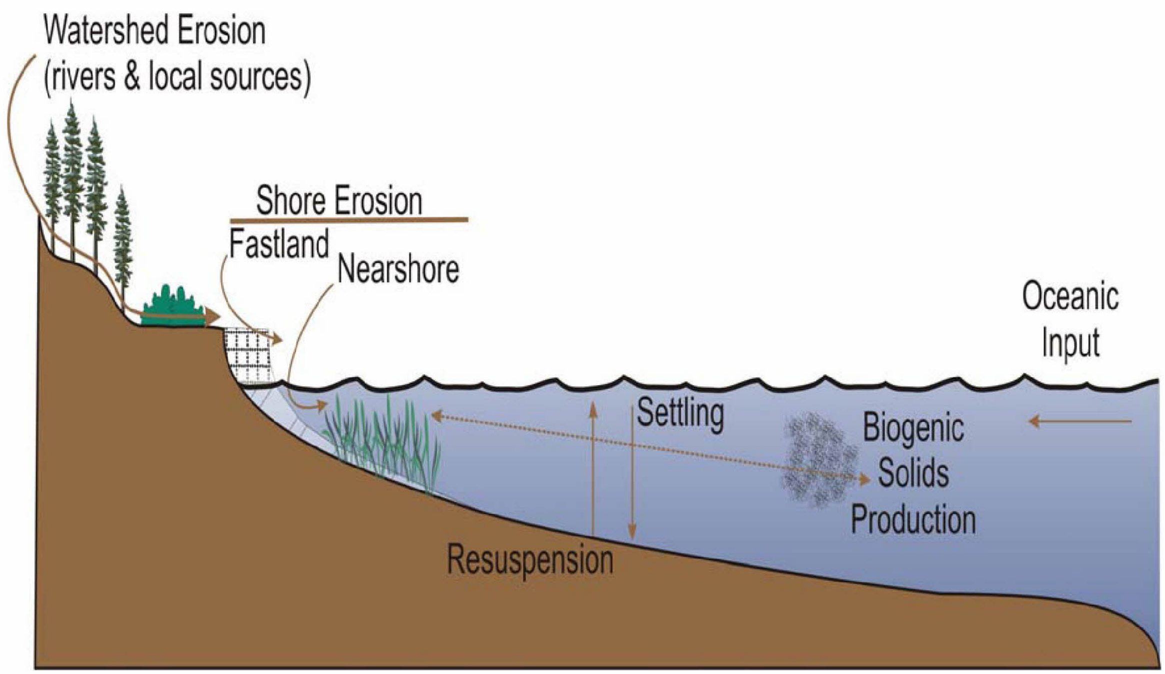

Figure 4-1. Conceptual model of sediment transport in nearshore region

Sections 4.1 though 4.6 provide an overview of the sources and the physical forcing processes that generate or remove sediment from the water column. Moreover, special discussion is provided for areas prone to the effects of sea level rise, and the estuarine turbidity maximum, a special case of combined resuspension and settling. Section 4.7 provides a preliminary estimate of Bay wide sediment source loadings based on existing literature and identifies sources with little or no available information.

4.2 Watershed Sources

A large proportion of sediment that enters Chesapeake Bay is ultimately derived from erosion in the Bay's watershed. Erosion from land surfaces and erosion of stream corridors are the two most important sources of sediment coming from the watershed. Watershed surfaces include land uses of cropland, mining areas, pasture, forests, suburban, and urban areas. The channel corridor consists of the channel bed, stream banks, and flood plain. Sediment erosion is a natural process influenced by geology, soil characteristics, land cover, topography, climate, and stream morphology. Rates of natural erosion are often affected by human activities, which lead to both increases and decreases in the erosion, transport, and deposition of sediment.

An example of accelerated rates of soil erosion occurred as a result of land-use practices associated with European colonization of the region in the 18th and 19th centuries (Wolman and Schick, 1967). Agriculture and timber production cleared as much as 70-80 percent of the original forest cover, and elevated erosion rates in the Bay's watershed, leading to a greater mass of sediment being transported to the Bay and its tributaries (Langland et al., 2003). During this period, thousands of dam and mill ponds for local industry also were constructed (Merritts et al., 2006). The construction of these dams and ponds caused a regional base-level rise and was an important cause of aggradation in the channel corridor (Merritts et al., 2004; 2006). The post-European derived sediment that was eroded and stored in many stream channels and behind former dams is referred to as "legacy sediment."

The trend towards deforestation peaked in the late 1800s and was reversed during the 20th century, when much of the watershed became reforested. Erosion rates should in theory have decreased during this period, but may have remained elevated for two reasons: (1) increases in urbanization, suburbanization, and associated construction practices, and (2) the removal of legacy sediment through bank erosion. Increased urbanization and suburbanization in the 1960s led to large-scale commercial and residential building, which denuded the landscape for a period of time and led to large increases in sediment yield (Wolman, 1967; Wolman and Schick, 1967).

Adjustments of stream channels, which can lead to bank erosion, are still occurring from historical and current modification of the landscape. For example, bank erosion has increased in many stream channels as a result of channel straightening or channelization for runoff control (Gellis et al., 2003). Channelization increases the channel slope and often leads to channel lowering (degradation) and channel widening (bank erosion). Urbanization increases the impervious area and leads to higher urban stormwater runoff and bank erosion. As aging mill dams breached or were removed, sediment stored behind the dams was eroded through bank erosion and transported by the newly formed active channel (Merritts et al., 2004; 2006).

Agriculture, construction practices, and streambank erosion are important sources of sediment in stream channels draining the Chesapeake Bay watershed (Langland et al., 1995; Langland et al., 2003). Some generalizations can be made about erosion, sediment yield, and land use within the Bay's watershed. For the entire Chesapeake Bay region, river basins with the highest percentage of agriculture have the highest annual sediment yields, and basins with the highest percentage of forest cover have the lowest annual sediment yields (Langland et al., 1995; Senus et al., 2004).

Urbanization can more than double the natural background sediment yield; the highest increase in sediment yield occurs in the early stages of land clearance associated with construction practices (Langland et al., 2003). Other activities also influence watershed erosion. Coal mining, for example, which has declined from historical levels in the watershed, still can contribute the addition of fine particles from "reworked" piles to rivers and can increase sediment yields by several orders of magnitude above background levels (Gellis et al., 2003).

Sediment remains an important pollutant to Chesapeake Bay, and along with nutrients, is decreasing water clarity and increasing light attenuation. For land managers to effectively reduce sediment loadings to the Bay, information on whether a particular part of Chesapeake Bay is influenced by Bay-derived sediment such as fastland or nearshore erosion or watershed-derived sediment must be obtained. If watershed-derived sediment is significant, then steps need to be taken to isolate the important tributaries and identify the important sources of this sediment within these tributaries. Although generalizations can be made about the major sources of watershed-derived sediment in a tributary, an effort should be made to effectively quantify sediment sources for tributaries in the Chesapeake Bay watershed. Without this information, land managers will not be able to adequately reduce sediment loads to Chesapeake Bay.

4.3 Shore Erosion

Shore erosion is the combination of both fastland erosion (land above tidal water, often called shoreline) and nearshore erosion (the shallow water close to the shoreline) (see Figure 4-1). Shore erosion should be viewed as an integral part of the natural ecosystem processes in the Bay and a necessary component of a properly functioning ecosystem. However, excess suspended sediment delivered from many sources, including shore erosion, is directly linked to degraded water quality and has adverse effects on critical habitats such as SAV beds and living resources such as shellfish and finfish in the Chesapeake Bay and its watershed (Langland and Cronin, 2003).

The wave energy that affects a shore is determined by the fetch, orientation of the shoreline relative to the prevailing winds, bathymetry, and storm wind directions. Offshore water depths and the presence of plants and animals such as SAV and oyster reefs can reduce wave energy levels. The ability of a given wave to erode a shore is influenced by the shoreline condition and sediment composition, and the presence of vegetation on the shore. In addition, there are factors not directly related to wave energy that influence shoreline stability, such as saturation of the sediment with water, watershed runoff, and the action of freeze-thaw cycles.

Fetch has been used as a simple measure of relative wave energy to categorize susceptibility to erosion forces. Low-energy shorelines have average fetch exposures of less than one mile and generally have low erosion rates. Medium-energy shorelines have fetch distances between one and five miles and commonly have higher erosion rates. High-energy shorelines, where fetch exceeds five miles generally have the highest erosion rates (Hardaway and Byrne, 1999).

The shoreline orientation relative to the fetch will modify the rate of erosion. Eastward-facing shorelines tend to have lower overall erosion rates than westward-facing shorelines because of the prevailing westerly winds in the mid-Atlantic region. However, storm events with associated east winds can result in dramatic erosion rates over the short term.

Similarly, offshore characteristics can modify and reduce wave energy. Shallow nearshore regions reduce the incoming wave energy more effectively than deeper water, and the presence of SAV can weaken wave action providing some shore protection. Additionally, shore erosion is also influenced by the bathymetry and the geomorphology of the area.

The composition and slope of a shore also affect erosion rates. For example, a gently sloping beach can withstand waves better than a vertical bank with no beach. The composition of the shore or bank also affects the rate of erosion. Compacted clays, naturally cemented sands and slopes that are heavily vegetated with root-mat forming plants resist erosion better than loosely consolidated sands or shores barren of vegetation. All of these factors combine to determine the erosion potential of any shoreline. Understanding these factors will provide better insight into a shoreline's vulnerability to erosion.

Special case - Areas Prone to Effects of Sea-Level Rise

Sealevel over geologic time is dynamic. The sea has been rising globally since the last Ice Age began to wane. The Bay itself formed as the rising sea flooded the Susquehanna River valley thousands of years ago (Colman et al., 1992). Variations in regional and local geologic and hydrologic conditions cause the rates of sea-level change to vary spatially. Within the Bay, areas underlain by sediments prone to compaction subside at a greater rate than adjacent areas that possess more stable subsurface materials. This has contributed to locally accelerated rates of sea level rise in Blackwater National Wildlife Refuge (Newell 2006). Additionally, groundwater withdrawal by people over the last century may have exacerbated subsidence in localized areas of the Bay such as in the Cambridge, MD area (Stevenson et al., 2000).

Sea level in the Chesapeake Bay has risen approximately 1.3 feet over the past 100 years, and is expected to continue to rise in the next century. Recent estimates suggest that this rate may increase to as much as 2-3 feet in the next 100 years (Leatherman et al. 1995). The rate of sea-level rise is forecast to increase with anthropogenic atmospheric greenhouse gas loading (Titus and Narayanan, 1995). As sea level rises, erosion increases because storm surges and waves batter retreating shorelines. Because of regional land subsidence and ocean warming, rates of sea level rise in the Chesapeake Bay and along the mid-Atlantic Coast are nearly double the global average (Langland and Cronin, 2003). The potentially large effect of sea level rise on erosion rates thus merits careful consideration in any comprehensive shore erosion control plan.

Sea-level rise drives shore erosion over the longterm, and gradually floods watershed and wetland areas, converting them to open water. Over the shortterm, shore erosion is driven by episodic storm events. The Bay has continuously grown in size throughout its geologic history (Stevenson and Kearney, 1996) due to the sea-level rise phenomenon. During the period of time spanning 1940 to 1990, fastland erosion claimed land at an average rate of about 460 acres per year in Maryland, based on shore erosion data compiled by the Maryland Geological Survey. Land loss occurred at a rate of about 300 acres per year in Virginia between the mid-1800s and mid-20th century, based on shoreline studies conducted by the Virginia Institute of Marine

Science. Additional landscape-scale conversion of interior marshes to open water also has occurred over this time period (Kearney et al., 1988; Kearney and Stevenson, 1991; Stevenson et al., 1985). Assuming that these trends persist today, the surface area of the Bay is likely growing at a current rate in excess of 1,000 acres per year in Maryland and Virginia.

Sea-level rise rates have varied over time in the Bay over the last several thousand years. Sea-level rise appears to have accelerated from a rate of about 1 mm/yr to a rate in excess of 3 mm/yr following the end of the Little Ice Age that ended in the 1800s. Shore erosion rates in the Bay appear to have increased concomitantly with the acceleration in the rate of sea-level rise (Kearney, 1996). However, recent tide gauge data exhibits a different trend. In the period between 1970-1990 changes in the regional ocean circulation and density structure has produced a temporary fall of sea level in the Chesapeake Bay that has entirely offset the effect of the subsidence due to postglacial rebound (NOAA). Thus over that period the net change of sea level in the middle Atlantic area was close to zero. "Of course this situation will not last. The nearby ocean will inevitably recover, and even overshoot, its long term rate of sea level rise in the area, producing at some time in the future (probably in the next few decades) a rate of rise that exceeds the long term average rate for the region."(NOAA).

Tidal marshes of the lower Eastern Shore are highly reliant upon accumulation of sediments and organic matter to maintain their surface elevation with respect to sea level. Marshes in these areas appear to be unable to keep pace with sea-level rise at current rates and are failing (drowning and or eroding and converting to open water) on a landscape scale (Kearney et al., 2002). Failing marshes in the Blackwater area generate substantial quantities of sediment which are exported to Chesapeake Bay (Stevenson and Kearney, 1988). Continued landscape-scale failure of marshes in the lower Eastern Shore could perhaps be forecast to deliver sediment loads to the Bay as a function of the rate of marsh failure. Figure 4-2 depicts areas most vulnerable to sea level rise. With acceleration in the rate of sea-level rise, it is likely that marsh failure rates would increase dramatically, increasing the rate at which sediment from these failing systems is delivered to the Bay. Increasing the available suspended sediment for input into these marshes could conceivably improve their ability to maintain pace with a rising sea level and thus maintain the habitat and reduce the export of sediment to the larger Chesapeake.

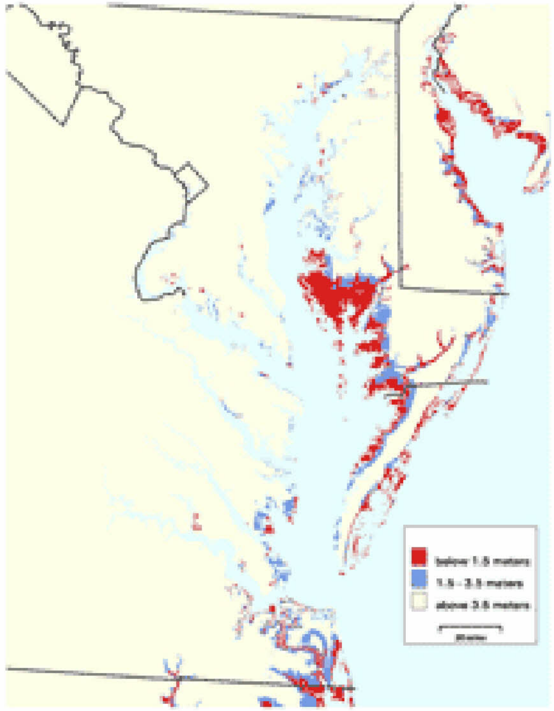

Figure 4-2. Areas Most Vulnerable to Sea Level Rise (Titus and Richman, 2001).

4.4 Oceanic Input

Sedimentation in the southern part of Chesapeake Bay has been the subject of numerous detailed studies over the past 40 years. In the southern Bay, large quantities of sediment are derived from inflow from the Atlantic Ocean continental shelf through the Bay's mouth due to tides and ocean currents, and from coastal erosion of headlands along the Bay margins (Harrison et al., 1967; Meade, 1969, 1972). The Bay mouth is characterized by complex sedimentary processes that result from variations in the tidal prism, fluvial input to the estuary, storm conditions in the estuary and in the Ocean, and mutually exclusive ebb- and flood-dominated channels (Ludwick, 1975). Estimates of sediment influx through the mouth have relied on bottom sediment sampling (Byrne et al., 1980), long-term averaging from geological and geophysical studies (Colman, et al 1988), mineralogical data (Bergquist 1986), and short-lived radioisotopic studies of sediment cores (Officer et al., 1984). Studies of long-term sedimentation in the southern Bay indicate that subsurface Holocene sediment filled the former Susquehanna River channel and that the majority of sediment entered through the Bay mouth as relatively coarse sands. The associated introduction of fine-grained sediments from the ocean source could not be identified by those methods, but conceivably could be large.

Analysis of successive bathymetric surveys conducted from the mid-1800's to the mid-1900's and analyses of bottom sediments show significant accumulations of sediment in the Bay mouth region relative to other portions of the Bay (Byrne and Anderson, 1977; Byrne et al., 1980;

Kerhin et al., 1988; Hobbs et al., 1990, 1992). These studies suggest that the volume of sediment that has accumulated in the Bay during the 1840-1940 periods cannot be accounted for solely from shore erosion, biogenic production, and riverine input. The volume of sand-sized sediment exceeded the available sources by a factor of between 2.7 and 7.6, the range being dependent on the levels of confidence that were ascribed to the bathymetric changes observed in comparing the historical surveys. Most of this difference in the sand-sized fraction of quantifiable sediment occurred in the Virginia portion of the Bay where most of the sand deposition occurs. Finer-grained muds exceeded quantifiable sources by a factor of 2.4, a value less than that for sands, but still large. Consequently, Hobbs et al. (1990) concluded that ocean-source sediment entering from the adjacent Atlantic Ocean through the Bay mouth must be a significant source of the total sediment deposited in the Bay. Colman et al. (1992) examined relatively long-term Holocene (10,000 year) depositional records for the mainstem of the Chesapeake Bay, and concluded that very large sediment volumes have been deposited in the Bay mouth area, northward to the southern end of Tangier Sound. These data on sediment inputs to the lower Bay indicate that the greatest sediment volume is from oceanic input from the continental shelf rather than the Susquehanna River and other watershed tributaries, averaged over Holocene time (Colman et al., 1992).

Although sand is the predominant sediment type in the southern Bay, the transport of fine-grained sediment northward from the southern regions, and from the mainstem Bay into larger tributaries, also can be a large source. In a comprehensive survey of the distribution, physical properties and sedimentation rates in the Virginia portion of the Bay, Byrne et al. (1982) concluded that channels leading to the James and York tributaries are mud as are the entrance channels and basin embayments of Mobjack, Pocomoke and Tangier Sounds. In addition, the deposition patterns suggest that there is appreciable transport of fine sand as a consequence of net up-Bay estuarine circulation through the deep channel along the eastern shore from the Bay-mouth region to at least 35 kilometers up the Bay (Byrne et al., 1980).

Several authors (Byrne et al., 1980; Hobbs et al., 1990) commenting on the sediment budget based on Schubel and Carter (1977), which could not account for the large volume of sediment deposited since the 1840's, postulated that

> *"If the tributaries are sinks for materials transported <u>from</u> the Bay, then the apparent discrepancies between bottom accumulation and the previous estimates of source strength are enlarged. If the tributaries are <u>sources</u> rather than sinks, and if the Bay mouth is a stronger source than previously estimated, then the order of magnitude discrepancy for silt and clay accumulation would be reduced."*

This conclusion suggests that significant amounts of finer-grained material are entering the Bay from its mouth, and also that the sub-estuary rivers are a potential source of fine sediment to the Bay. Evidence that finer-grained particles derived from the southern Bay, possibly from oceanic sources, reach even farther up the Bay was discussed in Hobbs et al., (1990) who, quoting the work of Halka, concluded that:

"Silts are transported much farther up-estuary than had previously been reported."

Other evidence supports the idea that, while sand-sized material dominates the surface sediments in the southern Bay, fine-grained clays and silts also are accumulating in some areas at a rapid rate. Officer et al. (1984) reviewed sediment flux rates for the entire Bay based on lead-210 dating of sediment cores and determined that sediment mass accumulation rates in the southern bay equaled those of the northern Bay where Susquehanna River inflow dominates as a sediment source. Studies of drift buoys also show that surface currents are capable of carrying fine-grained sediments from the Bay-mouth region far to the north. Harrison et al. (1967) showed that bottom drifters released on the shelf had been recovered as far north as Tangier Sound suggesting suspended material has the potential for transport relatively far up the Bay in the landward flowing denser saline water.

In summary, sediment in the southern Bay is derived mainly from the adjacent ocean with an unknown contribution from shore erosion along the Bay margins. These sources contribute to relatively high long-term sedimentation rates in the southern mainstem Bay and in adjacent sounds and embayments. Although much of the sediment deposited in the southern Bay is sand-sized, a portion is comprised of clay and silt-sized material and there is also good evidence for its significant net up-estuary transport. Because this material has the potential to influence water clarity in the Bay's shallow water bays and sounds, sediment transport and deposition in the southern Bay requires further study.

4.5 Resuspension and Settling

Bottom sediments in the Chesapeake Bay can be resuspended in response to tidal currents, waves, and boating traffic and can be a significant source of the sediment load in the water column. The amount of sediment introduced to the water column by resuspension is highly variable both spatially and temporally. Tidally resuspended sediments tend to occur as aggregated groups and thus settle back to the bottom quickly, only to be resuspended yet again in the next tidal cycle. Moreover, the ways physical forcing mechanisms generate resuspended sediment are complex, and the transport of the particles subject to resuspension, including their settling rates and eventual redeposition on the bottom, is only partially documented. In different parts of the estuarine system, the relative importance of tides, wind-generated waves and boating wakes on resuspension can be significantly different. It should be noted that the sediment concentrations in the water column resulting from resuspension are not from new sediment being introduced to the system, but are instead a recycling of material already in place.

The importance of tidal resuspension in fine sediment regions of Chesapeake Bay and its tributaries has long been recognized (Sanford and Halka, 1993; Schubel, 1968; Schubel, 1969). Recent work in the upper Chesapeake Bay demonstrated that asymmetrical tidal resuspension and transport are the primary mechanisms responsible for the maintenance of the ETM at the limit of salt intrusion (Sanford et al., 2001). Without the effects of tidal resuspension, the rapidly settling aggregates of fine particles would remain on the bottom. Below the ETM zone, in the mid-estuary, tidal resuspension is apparently weaker but still significant (Ward, 1985), although fewer detailed studies have been conducted in this region.

In an effort to examine the relative magnitude of tidal resuspension as an instantaneous source of suspended particulates in the upper bay, L. Sanford (University of Maryland, Center for Environmental Science, written communication, 2003) provided the Sediment Workgroup with an estimate of the amount of sediment resuspension that occurs on a daily basis in the northern Chesapeake Bay. The estimate is summarized herein because of its significance to the question of the potential importance of sediment resuspension to the suspended particulate load, but is only an estimate and only applies to the ETM zone where tidal resuspension is estimated to be most significant. The estimate is based on the volume of water in the ETM zone (from the mouth of the Susquehanna River south to Tolchester), the average background concentrations of suspended sediment, or that which is present irrespective of currents and bottom shear stress, and the resuspended sediment concentration in that water volume. Using these values, the suspended sediment load in the ETM zone is estimated to be approximately 135,000 metric tons (MT) during maximum tidal resuspension, including 90,000 MT of resuspended material per tidal cycle and 45,000 MT attributable to background concentrations. Given two tidal cycles per day, the estimated loading due to tidal resuspension is 180,000 MT per day, but this material also is redeposited twice per day. These values can be compared to the estimated combined input of "new" sediment to this area of the Bay from the Susquehanna River, shore erosion, and internal productivity of 4,400 MT per day. The relatively large value attributed to sediment resuspension is due to multiplication of a small number for suspended material per unit bottom area times the relatively large bottom area of the northern Bay. A few caveats apply to these estimates. The estimates were based on only a small number of study sites primarily in deeper waters of the ETM zone, such that the estimated total load of resuspended material must be considered very preliminary. It is not clear how much of the resuspended deepwater sediment can be transported laterally into shallower areas of the estuary, which is the general area of concern for improving water clarity. The process of deposition followed by resuspension with each tidal cycle results in the large total loads that are calculated, but it also results in relatively shortlived peaks in resuspended sediment concentration that are most pronounced near the bottom. Despite the uncertainties, a major conclusion that can be drawn from these estimates is that normal bottom-sediment resuspension processes could be the dominant instantaneous source for the suspended sediment load in the water column, when considered in a highly averaged spatial context.

Wave-forced resuspension coupled with wave-induced nearshore erosion in shallow (less than 2 m deep) parts of the estuarine system generally is understood to produce significant amounts of suspended sediment in the water column. However, relatively few site-specific studies of this topic have been conducted to date (Wilcock et al., 1998). Those that are available are applicable only to a particular location and time frame. Their results cannot be extrapolated to the larger estuarine system due, in part, to the variable geometry of the Chesapeake Bay that results in both variable fetch and wide ranges in nearshore bathymetry. Fetch influences the ability of local winds to generate waves; local variations in bathymetry influence the direction and energy of waves approaching shallow-water zones and shorelines. In the relatively deeper waters of the Chesapeake system, wave-forced resuspension may be significant under storm conditions and can dominate the normal tidally induced resuspension signal (Sanford, 1994; Ward, 1985; Wright et al., 1992). After the physical forcing associated with the storm wave energy is reduced, the resuspended sediments settle rapidly to the bottom, but these sediments exhibit increased erodibility for some period of time thereafter (Sanford, 1994), thus increasing the likelihood of subsequent transport by lower energy tidal currents. A similar dependence of bottom-sediment grain size with storm-wave bottom shear stress has been observed in intermediate water-depths in the Chesapeake Bay (Nakagawa et al., 2000). In that study, the bottom-sediment grain size was related to strong wind events that occurred less than 5% of the time, not to the mean wind speed for the area. The results of these studies point to the importance of infrequent high-energy events in sediment resuspension, transport, and eventual distribution on the bottom of the Chesapeake Bay. The influence of wind-wave induced bottom shear stresses on sediment resuspension and subsequent transport can probably only be estimated for local stretches of shoreline and on a bay-wide basis through the use of modeling simulations.

In the vicinity of the Bay mouth, long-period waves entering from the Atlantic Ocean are likely to resuspend more bottom sediment than shorter period storm waves further up the estuary (Boon et al., 1996; Wright et al., 1992), introducing another variable forcing mechanism influencing sediment resuspension. These externally derived waves would be temporally variable depending on conditions in the Atlantic Ocean, and their spatial influence in the Bay would vary depending on the wave period. Following passage of a significant long-period wave event, bottom sediments exhibit increased erodibility for some period of time as was noted following storm events further up the Bay (Sanford, 1994).

In addition to natural processes of waves, currents, and tides, boating activity also can cause sediment resuspension. A study of boat-wake effects on shore erosion in an area of high recreational boat use showed that boat wakes generated less incident energy than normal wind-generated waves (Zabawa and Ostrom, 1980). The major factor influencing shore erosion was a single storm event during the study period, followed by wind waves associated with normal wind levels. Recreational boating undoubtedly has increased throughout the bay region since that study, but it remains unclear how significant the effect of boat wakes may be on resuspension in nearshore areas. It is possible that larger effects result from repeated generation of boat wakes during periods of high recreational vessel use, such as summer weekends. Resuspension effects resulting from the passage of large commercial ships has not been studied in the Chesapeake and could be locally important because of the higher energy waves produced by these ships. However, the relatively infrequent passage of these ships would suggest that their importance is minimal relative to wind-generated waves.

In summary, the ability to control resuspension in the Chesapeake Bay that results from tidal currents and storm-generated waves is limited because of the extremely widespread sediment source (for example, the entire bay bottom). However, the processes that lead to sediment resuspension and subsequent transport into sensitive habitat zones need to be more fully understood through direct measurement coupled with the development of computer models that simulate resuspension in response to known physical mechanisms. With appropriate parameterizations representing sediment resuspension, deposition, and consolidation, these models could provide an understanding of where management actions can be most effective.

Estuarine Turbidity Maxima Zone (Secondary source and sink)

The northern mainstem bay and larger tidal tributaries each have an estuarine turbidity maximum (ETM) that results from a complex interaction of physical, chemical and biological processes. In this region, the amount of suspended material in the water column is higher than in either the upstream direction, toward the watershed, or the downstream direction, toward the mouth of the Bay. As a result light attenuation is enhanced in the water column, and the deposition of sediment to the bottom is greater than in many other portions of the estuary. See figure 4-3 for locations of the ETMs.

Early studies suggested that this zone of elevated turbidity resulted when clay particles, delivered in the fresh water flow, underwent electro-chemical flocculation at the junction of fresh and salt waters. In the Chesapeake, early seminal studies attributed the formation of the ETM to the relatively simple convergence of the estuarine gravitational circulation at, or near, the limit of salt intrusion (Schubel, 1968a; Schubel, 1968b; Schubel and Biggs, 1969; Schubel and Kana, 1972). In the ensuing years, investigations have identified a number of attendant physical processes that contribute to the formation and presence of ETMs in a variety of estuaries. Resuspension of bottom sediments by asymmetrical near-bottom currents (Dyer, 1988; Dyer and Evans, 1989), suppression of upward mixing by density stratification (Geyer, 1993), and the presence of a pool of available resuspendable particles (Uncles and Stephens, 1993) are physical processes that have been shown to contribute to the development of ETMs. In virtually all cases, these ETMs have been located near the upstream limit of salt water intrusion in the estuaries. In the northern mainstem asymmetrical tidal resuspension and asymmetrical tidal transport of rapidly settling aggregates are primarily responsible for the Chesapeake Bay ETM (Sanford et al., 2001).

Each of the major Chesapeake tributary systems has been shown to have an ETM zone near the upstream limit of saltwater intrusion. Examples have been noted in the Rappahannock (Nichols, 1974), the Potomac (Knebel et al., 1981), and the York Rivers (Lin and Kuo, 2001). Analyses of Chesapeake Bay water-quality monitoring data sets for the Sediment Workgroup identified the appearance of similar turbidity maxima zones in most of the main tributaries (Potomac, Chester, Patuxent, Choptank, Rappahannock, York, James and Elizabeth) (David Jasinski, unpub., 2006).

In contrast to the normal location near the upstream limit of salt water intrusion, interactions between the cross estuary bathymetry and circulation patterns have been shown to maintain a zone of elevated turbidity in the Hudson estuary, downstream of the salt limit (Geyer et al., 1998). The York River has been shown to have more than one ETM zone, one of which is well downstream of the salt front, probably because of multiple convergent transport zones (Lin and Kuo, 2001). The specific physical processes contributing to the development, maintenance and location of ETMs probably differ between estuaries, depending on specific conditions in each case. The dominant physical process governing the ETM location may change within the same estuary at different times of the year, in response to changing fresh water input, spring verses neap tides, wind forcing and season, among other factors.

Recent studies have shown that ETMs are areas of elevated zooplankton concentrations (Kimmerer et al., 1998; Morgan et al., 1997; North and Houde, 2003; Roman et al., 1988; Simstead et al., 1994). Abundant food in the form of detritus, protozoa, and phytoplankton, in addition to the physical processes described above, are thought to support the high zooplankton abundances. The protozoa, phytoplankton and zooplankton all contribute to the pool of suspended material in the ETM, and to the attendant light attenuation, although this impact may be strongly seasonal. Schubel and Kana (1972) found that zooplankton fecal pellets were important agents of particle agglomeration in upper Chesapeake Bay, enhancing the settling of particles during particular seasons.

Sanford et al. (2001) determined that in the mainstem Chesapeake the convergence of fresh and saline waters and its associated salinity structure contributed to strong tidal asymmetries in sediment resuspension and transport. These asymmetries collected and maintained a resuspendable pool of rapidly settling particles near the salt limit. The rapidly settling particles, primarily present in near-bottom waters, consisted of aggregations of finer particles which individually would have lower settling velocities. Without tidal resuspension and transport, the Chesapeake Bay ETM would either not exist or be greatly weakened. Repetitive resuspension suggests that the high suspended loads in the ETM are maintained not simply by continued introduction of new sediment, but also by repetitive reworking of the sediment already present. Resuspended sediments tend to be more aggregated and thus settle back to the bottom quickly, only to be resuspended yet again in the next tidal cycle, and as a consequence they tend to be located near the bottom. In spite of this repeated resuspension, sedimentation is the ultimate fate of most terrigenous material delivered to the Chesapeake Bay ETM. Sedimentation rates in the ETM channel are at least an order of magnitude greater than on the adjacent shoals, probably due to forcing mechanisms that are poorly understood. Ultimately, deposition of sediment to the bottom in the ETM zones removes these materials from the suspended load that affect water clarity.

The distinction between more rapidly settling aggregations of particles in the ETM zone and the more slowly settling finer particles is an important factor to remember. Total suspended sediment concentrations in the entire upper Bay are elevated relative to the rest of the estuary, with typical background concentrations of the very slowly settling particles ranging between 5–25 mg/l (Sanford and Halka, 1993; Sanford et al., 1991; Sanford, 1994; Schubel, 1968a; Schubel, 1968b; Schubel, 1971). These background particles tend to be uniformly distributed through the water column or slightly more concentrated in the lower water column. The ETM itself typically has TSS concentrations 20–100 mg/l higher than this background, with the largest concentrations resulting from tidal resuspension in the near-bottom waters. There is little spatial or temporal variation in the dispersed, or disaggregated, slowly settling particle size distributions (Sanford et al., 2001; Schubel, 1968a; Schubel and Kana, 1972). However, settling velocities of the aggregated particles in the ETM can exhibit seasonal variations with much higher settling rates in the warmer months relative to colder periods (Sanford et al., 2001; Schubel, 1968a; Schubel and Kana, 1972).

The presence of a background population of slowly settling particles throughout the water column suggests that some portion of the suspended materials bypass the ETM zone and enter the middle and lower portions of the estuarine system. North et al. (2004) showed that increases in both fresh water input and along-channel winds resulted in enhanced sediment transport down-estuary. Only reductions in river flow resulted in consistent up-estuary movement of bottom sediment in the ETM. Major flood events serve to not only mobilize and transport large quantities of sediment from the watershed for delivery to the tidal waters, but also translate the ETM zone into the middle portions of the system, well beyond the normal location. In the mainstem bay, Schubel and Pritchard (1986) estimated that the ETM zone can migrate 40-55 km seaward during flood events, which would lead to southward export of Susquehanna River sediment. During these events (e.g. Tropical Storm Agnes in 1972), which have been shown to deliver a disproportionately high sediment load, the majority of the delivered sediment bypasses the normal location of the ETM, allowing sediment to "escape". Satellite data also show export of suspended material from tributaries into the bay during relatively wet periods (Stumpf, 1988) at least in the upper portions of the water column.

Various studies have indicated more sediment may be "escaping" the ETM zone than generally believed. For example, geochemical tracer data indicate sediment has been transported over longer time scales than current studies would indicate, resulting in the delivery of sediment from the northern bay at least to the midbay (Darby, 1990; Helz et al., 2000). Using isotopic analyses of sediments from the central mainstem bay, Helz et al. (2000) concluded that the source of some mid-bay sediment was the Susquehanna River. Recent studies of sediment deposition rates in the central Chesapeake Bay by the USGS compared rates from the post-1880 and pre-1880 time periods (Langland and Cronin, 2003). While there was a great spatial variability throughout the Bay some sites exhibited about a four-fold greater sediment flux during the last century than during the prior 1,000 years, confirming the general conclusions of studies of sediment cores for the central mainstem discussed by others (Colman and Bratton, 2003; Cooper and Brush, 1993; Cronin et al., 2000). These results strongly suggest that the increased sediment loads, delivered from the watershed due to land-use practices since European occupation, have bypassed the ETM into to the middle portions of the estuarine system. The relative proportions of sediments that are retained in the ETM verses those that are transported down-estuary are difficult to establish.

In summary, while a number of processes that contribute to the formation, maintenance and location of the ETM are generally understood, there remains a variety of questions concerning the effectiveness of the ETM to serve as a sediment trap for the estuary. For example, we don't know many of the details of the following processes, all of which determine what happens to a fine-grained bit of inorganic material when it enters the Bay:

- How are fine-grained sediments aggregated in the fresh to brackish transition of the ETM?
- What are the sizes and settling velocities of aggregated particles, and how different are they from individual particles?
- How often do these aggregated particles become disaggregated under turbulent flow, and how quickly do they re-form?
- How large is the effect of filter-feeding organisms on particle aggregation and settling, relative to other processes?
- What role does organic 'stickiness' play in aggregation, and how seasonal is it?
- What specific shear stresses are required to resuspend particles once on the bottom, and how much seasonal variability is there?
- What controls the critical stresses for resuspension?
- How much sediment is available for resuspension at a given level of stress, and how does this quantity vary with sediment loading, physical forcing, and biological activity?
- After it initially settles to the bottom, how much time elapses before a particular sediment particle can be considered to be a permanent part of the bottom?
- If a particle that can be considered part of the permanent bottom experiences a significantly elevated shear stress due to a storm and is resuspended, under what conditions does it resettle to the permanent bottom?
- Once resuspended, what are the vertical and horizontal extents of particle transport in the post-1880 and pre-1880 time intervals?

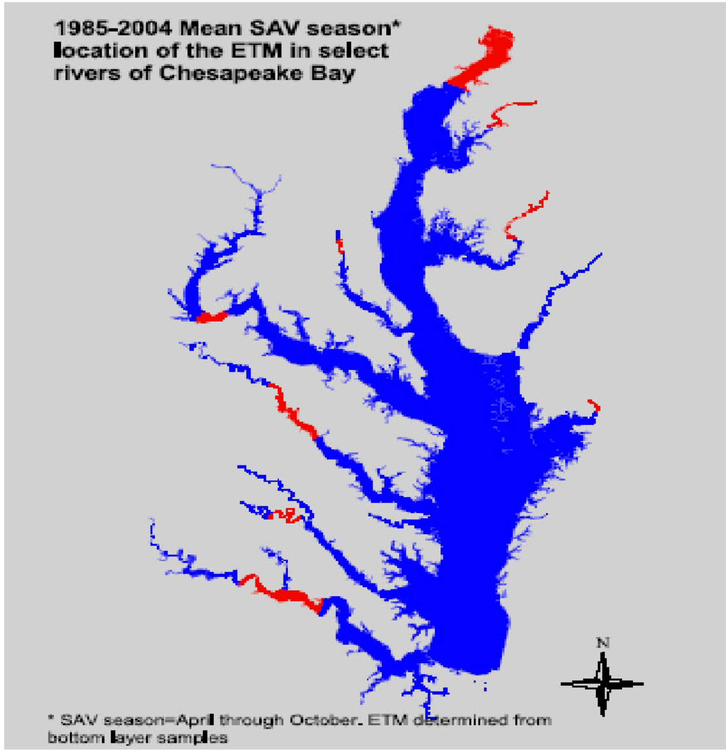

Figure 4-3 SAV growing season ETM locations (Source: David Jasinski, (UMCES, 2006))

4.6 Biogenic Sources of Sediment

Biogenic sediments generated within Chesapeake Bay itself can be broadly defined as any material consisting of the remains of organisms generated within the estuary by skeletal formation or organic production. This would include diatom siliceous skeletal material, dinoflagellate cysts, calcareous shells of benthic organisms (mainly foraminifera, ostracodes, mollusks), sponge spicules (siliceous), fish scales and bones (mainly phosphatic), and organic matter formed in situ. Diatoms, for example, can constitute 5-10 % of dry sediments, calcareous shells as much as 5 %. Biogenic suspended matter of most concern in terms of water quality can be viewed as those components that occur in the water column, mainly phytoplankton (diatoms and dinoflagellates) and zooplankton. Historically increasing turbidity in the bay, due in part to biogenic suspended matter, has been hypothesized as a contributing factor to the decline in SAV for at least 20 years (Orth and Moore, 1983).

A review of the literature on biogenic components of sediment in Chesapeake Bay can be summed up in two contradictory conclusions. In a comprehensive bay-wide review of sediment characteristics in the bay and its tributaries, which provided quantitative estimates of sediment sources and budgets, Nichols et al. (1991) concluded that biogenic production and consumption were "neglected since they are usually small." If one accepts this conclusion, and in light of the lack of biogenic sediment data in most previous studies of Chesapeake Bay sediments, it would at first appear that in situ-generated suspended matter is not quantitatively significant in the overall sediment budget of the bay.

Conversely, in one of the few studies to consider the composition of suspended sediments in the bay, Biggs (1970) concluded from analyses of suspended sediment that skeletal material and organic production contributed 18% and 22% respectively to suspended matter in the mid Bay. In the northern Bay these values were only 2% being overwhelmed by riverine input from the Susquehanna River. Biggs did not consider the southern Bay. An extensive literature search published since the studies of Nichols et al. and Biggs suggests that biogenic material is an important component of suspended matter in the Bay and has increased significantly in the last several decades. First, overall organic productivity (driven by nutrient influx, including silica) has increased substantially during the 20th century based on trends in chlorophyll *a* (Harding and Perry, 1997), biogenic silica (Cooper and Brush 1991; Colman and Bratton, 2003.), diatom floras (Cooper, 1995), dinoflagellates (Willard et al. 2003), and organic biomarkers (Zimmerman and Canuel, 1999). Second, much of this increase has occurred since Biggs conducted his study, which was based on data collected in the 1960s, suggesting the biological component of Chesapeake suspended matter is in all likelihood progressively increasing, although seasonal and interannual variability is great. Third, biological processes play an important role in the production, transport and fate of particulate sediment within and downstream of the estuarine turbidity maxima of the Bay and its large tributaries (Kemp and Boynton, 1984; Fisher et al., 1988), in concert with tidal re-suspension and other processes (e.g., Sanford et al., 1991). Organic-inorganic coupling greatly affects particle settling time which, in concert with physical processes, will determine whether material is deposited in the ETM, advected laterally, or transported downstream of the turbidity maximum zone. Ultimately, these processes affect water quality in large parts of the northern Bay and under certain conditions the mid-Bay as well.

In sum, in situ biological processes, fueled by external nutrient influx, modulated by climate and river discharge variability, and influenced by estuarine circulation, tides and wind, contribute significantly to water clarity, suspended sediment, sedimentation, and bottom sediment composition. Well-documented temporal trends of the past century in organic production, phytoplankton ecology, riverine nutrient and sediment influx, although not usually considered in analyses of Bay sediment, suggest that biological components of Chesapeake Bay sediment are even more important than they were 40-50 years ago. Quantitative estimates of the relative contribution of biogenic material, both as organic matter and skeletal materials, to the suspended load in various regions of the Bay cannot be made with certainly based on current data. It is likely that efforts to reduce nutrient influx would improve water clarity by reducing biogenic sediment.

4.7 Sediment Source Loadings

The following table attempts to assemble the available information that can lead to developing a full sediment budget for the Chesapeake Bay. The data was derived from available regional or comprehensive information sources. It is presented primarily to provide an indication of the approximate relative sediment contributions from the major sources, and the degree of convergence or divergence between the values reported in those sources. The implicit assumption being that where values converge between sources there is a greater degree of confidence in the validity of the value for that input source. A number of the rows are devoid of entries because no reliable comprehensive estimates have been produced. However, they are included to indicate additional research studies or monitoring efforts requirements to understand the range and magnitude of sediment sources.

Values are in metric tons per year of fine-grained sediments, or silt- and clay-sized particles finer than 63 microns diameter. Because the focus of this effort centers on sediment and light attenuation, the mass of coarser sand sized particles is not included. Sand-sized sediments are assumed to have limited transportability in the water column either temporally or spatially, with movement in the estuary occurring primarily by bed load transport mechanisms. As such sand-sized particles have limited impact on water clarity issues.

Table 4-1. Chesapeake Bay Sediment Source Loadings (metric tons per year)

	Current Model Estimates: Phase 4.3 Watershed and 2002 Eutrophication [a]	Updated Model Estimates: 2008 Eutrophication (draft)	1990 COE Shore Erosion	RIM data[b] (all available years)	Other [c]	Sediment WG Report (Chapters 5 and 7)
Watershed (Above Fall Line)	4,359,721	X	X	5,328,000	X	4,270,000
Watershed (Below Fall Line)	1,467,429	X	X	296,000	425,686	900,000
Shore Erosion [d]	4,667,000	2,009,000	~12,000,000 (reported as volume of 8,411,000 m^3)	X	X	8,420,000
Oceanic	606,000 (960,000 import 354,600 export)	X	X	X	470,000	1,140,000 [e]
Direct Atmospheric Deposition	X	X	X	X	X	14,000

Resuspension and Settling	X	X	X	X	X	X
Biogenic Sediment Production	X	X	X	X	X	X

X indicates no data for that source from the identified study/effort.

Notes:

a: Phase 4.3 Watershed model and 2002 eutrophication– uses 1985-1994 hydrologic period for watershed inputs.

b: RIM data – Most recent data obtained from web, includes all years of estimates (1981-2005 for Susquehanna; Potomac; Patuxent, Choptank; 1989-2005 for James, Rappahannock, Appomattox; 1990-2005 for Pamunkey, Mattaponi) with no attempt to utilize same hydroperiod as the Phase 4.3 Watershed model; scaled as follows.
Above Fall Line (AFL) – Averaged delivery for all RIM stations excluding the Choptank scaled up to the size of the entire AFL watershed (RIM AFL stations cover 129,300 km^2 or 78% of AFL watershed area).
Below Fall Line (BFL) – Averaged delivery for RIM Choptank River station scaled up to the size of the entire BFL watershed. (Choptank RIM station covers 290 km^2 or 0.8% of the BFL watershed area).

c: Other –
BFL - from A. Gellis, 2006, personal communication. Average sediment delivery of 11.9 metric tons/km^2/yr derived from all available stream gauge data in BFL watersheds. Multiplied by BFL area of 35,772 km^2.
Oceanic - from Schubel and Carter (1977) based on conservative salt model

d: Shore Erosion – For all studies except 2002 Eutrophication Model, consists of fastland erosion and the associated nearshore erosion in the area immediately offshore of the eroding fastland. Nearshore erosion is estimated from a constant ratio to the adjacent fastland erosion. The 2002 Eutrophication Model used only the fastland component.

e: Oceanic input identified in Sediment Workgroup Report (Langland and Cronin, 2003) adapted from Hobbs et al. (1992). Estimated as difference between reported sources and mass needed to balance amount of sediment accumulated based on bathymetric changes.

5 Analysis of Chesapeake Bay Sediment-Related Monitoring Data

5.1 Background

An exploratory analysis of Baywide long term monitoring data was conducted using suspended sediment-related water quality information. The purpose of the analysis was to identify similarities between Bay water quality segments and then cluster them to gain an understanding of which groups of segments had similar sediment-related effects or designated use impacts. It is expected that the results of this analysis could be used to prioritize model scenario runs for sedimentshed delineation by identifying areas where water clarity is potentially most impacted by inorganic sediment.

The Sediment Workgroup discussed the most appropriate dataset for the analysis, the most appropriate temporal period for averaging the data and finally the potential parameters to be included. It was decided that SAV growing season data from the Chesapeake Bay long-term monitoring stations (Figure 5-1) would be used in this analysis as this would be the most comparable in terms of data quality and available information. It was further concluded that surface layer results would be used since these are most consistent with the application depth of the water clarity criteria. The final set of parameters used in the cluster analysis was salinity, the light attenuation coefficient, and percent of fixed suspended solids. Please note that this final selection is still under review by the Sediment Workgroup.

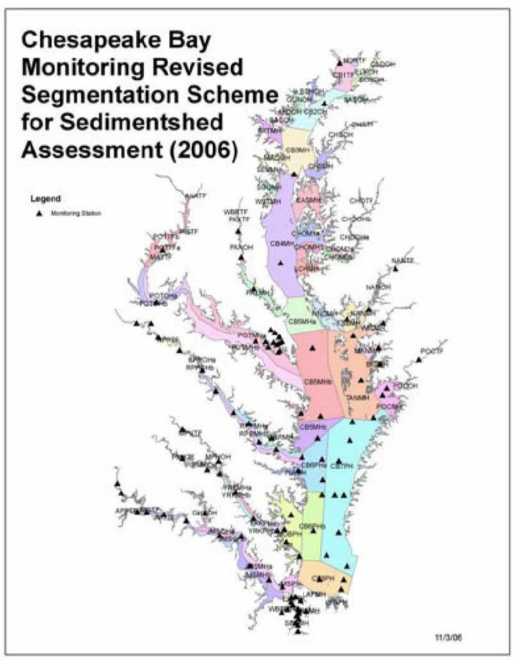

Figure 5-1. Chesapeake Bay monitoring station locations and revised monitoring scheme. (John Wolf, 2006).

Salinity and the light attenuation coefficient were selected because they are the basis of the water clarity criteria. It was reported that SAV is most sensitive to the available light through the water column and that the required light to support SAV varies as a function of salinity. More saline SAV species require more light whereas less saline SAV species require less light, relatively speaking, for survival (see Figure 5-2). The percent of fixed suspended solids was used because it represents the actual sediment contribution to the total suspended solids in the water column. Fixed suspended solids represent the inorganic solids and are composed of clay, silt and sand whereas volatile suspended solids represent the organic solids derived from nutrients (eg. phytoplankton chlorophyll *a*, organic detritus).

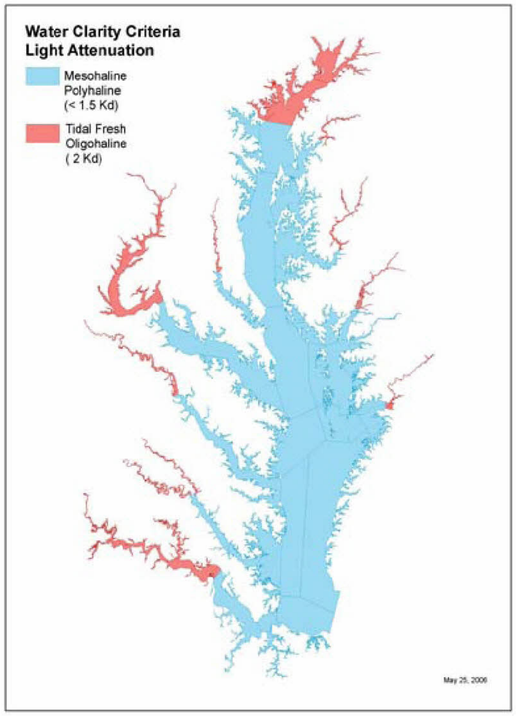

Figure 5-2. Light attenuation water quality criteria in the Chesapeake Bay. (CBPO, 2005).
In the mesohaline and polyhaline regions, SAV is able to grow if the light attenuation coefficient is less than 1.5. In the tidal Fresh and oligohaline regions, SAV can withstand more turbid water, and needs a light attenuation coefficient of less than 2.0.

Two options were considered for input units into the cluster analysis. First, the clustering analysis could be based on results at the monitoring stations and second, using the Bay monitoring data interpolator program, results could be interpolated and extrapolated throughout the Bay and then averaged to a user-defined scale. While the first is more robust to the original data, the second option allowed for more flexibility given the regulatory considerations of working within the Bay water quality segments. It was therefore decided the average SAV growing season monitoring station results would be interpolated and extrapolated throughout the Bay. However, it must be recognized that even though we have estimated values along the shoreline, these values are only representative of those at main channel locations (i.e. the original monitoring stations).

The spatial units for averaging the monitoring data results were based on the Chesapeake Bay water quality segments. This is the scale that has been adopted into regulation by the Bay states. Adjustments to these segments were made for this analysis only, and included splitting several of the larger main bay segments to capture the effects of the nearby tributary influence and splitting segments near the growing season estuarine turbidity maximum as determined by Jasinski (2006). The final segments are illustrated in figure 5-3. The segment-averaged results for salinity, light attenuation and fixed suspended solids are presented in figure 5-4.

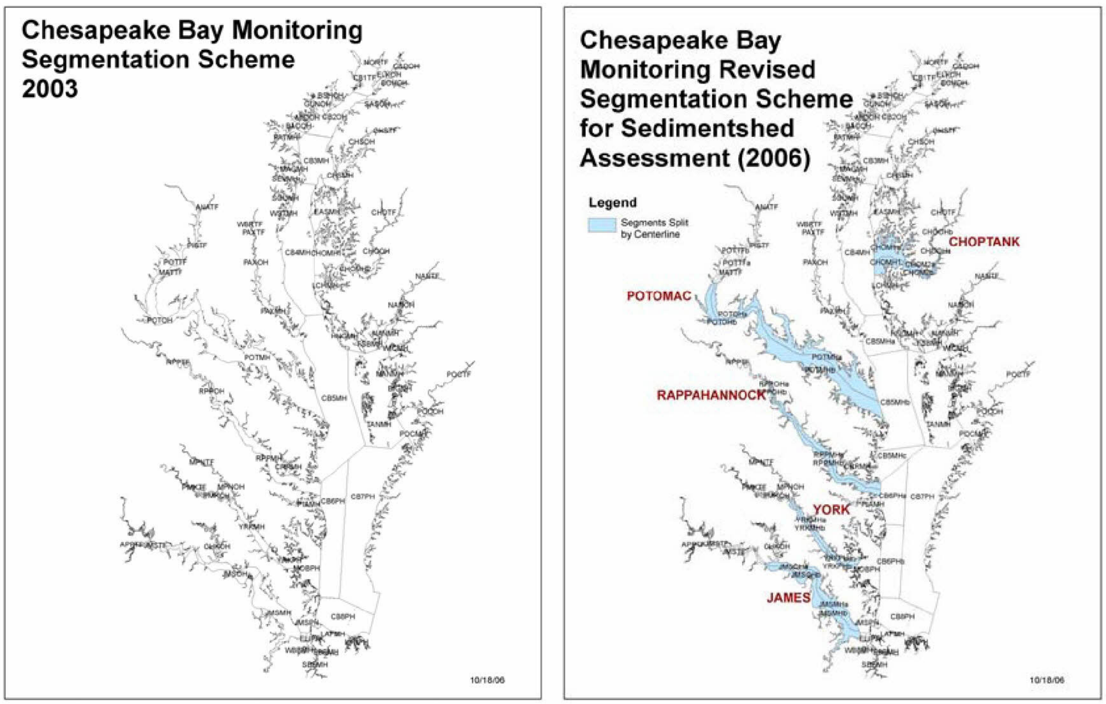

Figure 5-3. Adjustments to Bay Water Quality segmentation for cluster analysis

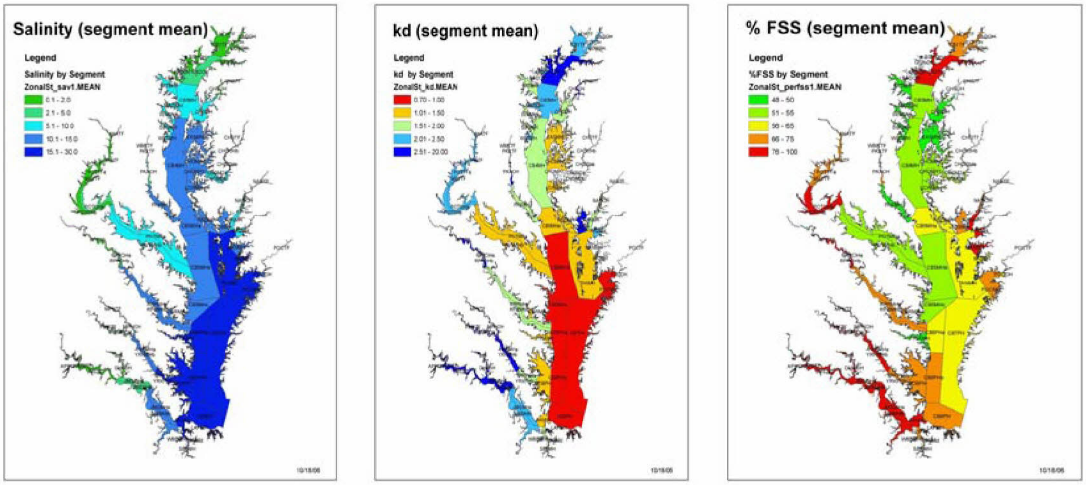

Figure 5-4. Segment-averaged values for salinity, light attenuation and percent fixed suspended solids (Jasinski and Wolf, 2006).

5.2 Clustering Methodology

Hierarchical cluster analysis was performed in SAS using the centroid method on squared Euclidean distances. The centroid method was selected because it tends to be more robust to outliers than most other hierarchical cluster procedures (Milligan, 1980). Input data for the analysis were scaled to a mean of zero and a variance of one to allow for equal representation among the three parameters when computing the distances.

Clusters were selected by moving down the resulting dendogram (Figure 5-5) to separate major groupings, which ideally contained multiple Bay water quality segments. The appropriate number of clusters was confirmed using the cubic clustering criterion (CCC), pseudo F, and pseudo t^2 statistics output in SAS (Lipscomb, 1998). Based on a local maximum of the CCC and changes in the pseudo t^2 statistic seven clusters were identified.

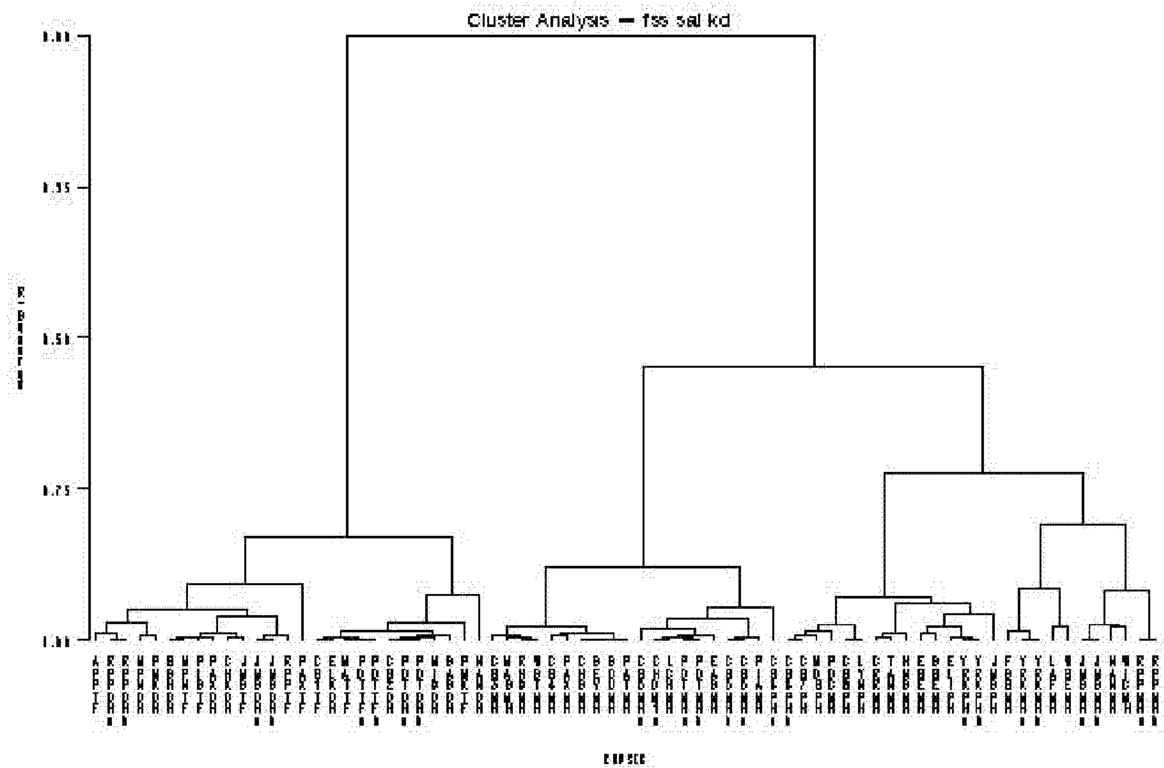

Figure 5-5. Dendogram of hierarchical cluster analysis using salinity, light attenuation and fixed suspended solids (Lee Currey, 2007)

5.3 Cluster Results

The cluster analysis revealed seven distinct clusters that capture approximately 91% of the variance in the data. The number of segments per cluster ranged from five to fifteen. Salinity was a significant parameter in splitting segments and defining clusters. This was expected and also intentional, with the purpose to group regions that have a similar water column water clarity criteria.

The tidal fresh and oligohaline regions of the Bay resulted in two clusters, which were differentiated primarily by light attenuation with some additional influence from fixed suspended solids. Higher light attenuation and fixed suspended solids in cluster 2 included the Rappahannock, Mattaponi, Pamunkey and James. Cluster 1 had slightly lower light attenuation and slightly lower fixed suspended solids and included the Upper Bay and Upper Potomac River.

The mesohaline region of the Bay resulted in four clusters (3, 4, 5, 6) with varying levels of light attenuation. Of the four clusters, three of the clusters (3, 5, 6) exceeded the light attenuation water clarity criteria. Of the three clusters exceeding the light attenuation criteria, two had high fixed suspended solids (5, 6) and one cluster (3), located in the upper part of the Bay and below the estuarine turbidity maximum, had relatively low fixed suspended solids. Using the percent fixed suspended solids, it would be possible to aggregate these four clusters into two clusters, with one having high fixed suspended solids (5, 6) and the other relatively low fixed suspended solids (3, 4).

Cluster 7 mostly consisted of polyhaline Bay water clarity segments with relatively moderate levels of fixed suspended solids. In addition, the majority of the segments had an average light attenuation coefficient below the water clarity criteria, thus meeting water clarity standards.

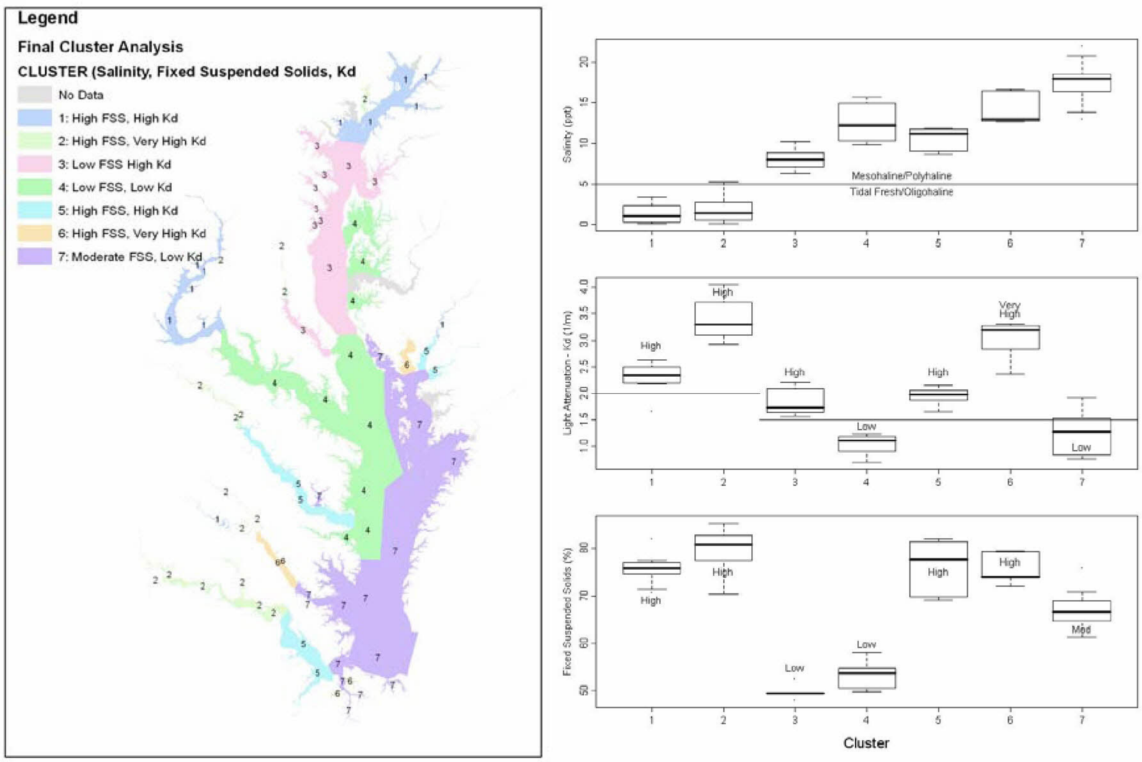

Figure 5-6. Cluster results – Segmentation map and corresponding box and whisker plots per cluster (Lee Currey, 2007).

Simplification of the results presented in Figure 5-6 is further possible by aggregating clusters by using a categorical classification for light attenuation and percent fixed suspended solids. Clusters exceeding the light attenuation criteria were assigned a classification of high or very high and clusters below the criteria were assigned a classification of low. Similarly, the clusters were assigned fixed suspended solids classifications of low, moderate and high based on a relative comparison. Categorical results are illustrated on the box and whisker plots in Figure 5-6. Based on these classifications it is possible to identify regions that are exceeding the water clarity criteria and that also a have relatively high percent of fixed suspended solids (1, 2, 5, 6), thus indicating an impact from sediment. Clusters 3 and 7 exceed the water clarity criteria yet have low to moderate levels of FSS, indicating that the water clarity impairment may be caused by factors other than, or in addition to, FSS. Results of this final grouping are presented in Figure 5-7, with a comparison to the water quality modeling results presented by Cerco et al. (2002) that identify areas that benefit more from sediment controls (shaded area) than from nutrient controls in the watershed and tidal tributaries. These two maps essentially identify the same regions.

Although there is good correspondence between the results of this cluster analysis and those presented by Cerco et al. (2002), it is important to recall that the monitoring data used in the clustering is based on main channel stations. While in many regions of the main Bay the monitoring data showed a low light attenuation coefficient, it is expected there may be more variability between the main channel and near shore environment and these results should be confirmed using the shallow water monitoring data that are currently being collected by Maryland and Virginia.

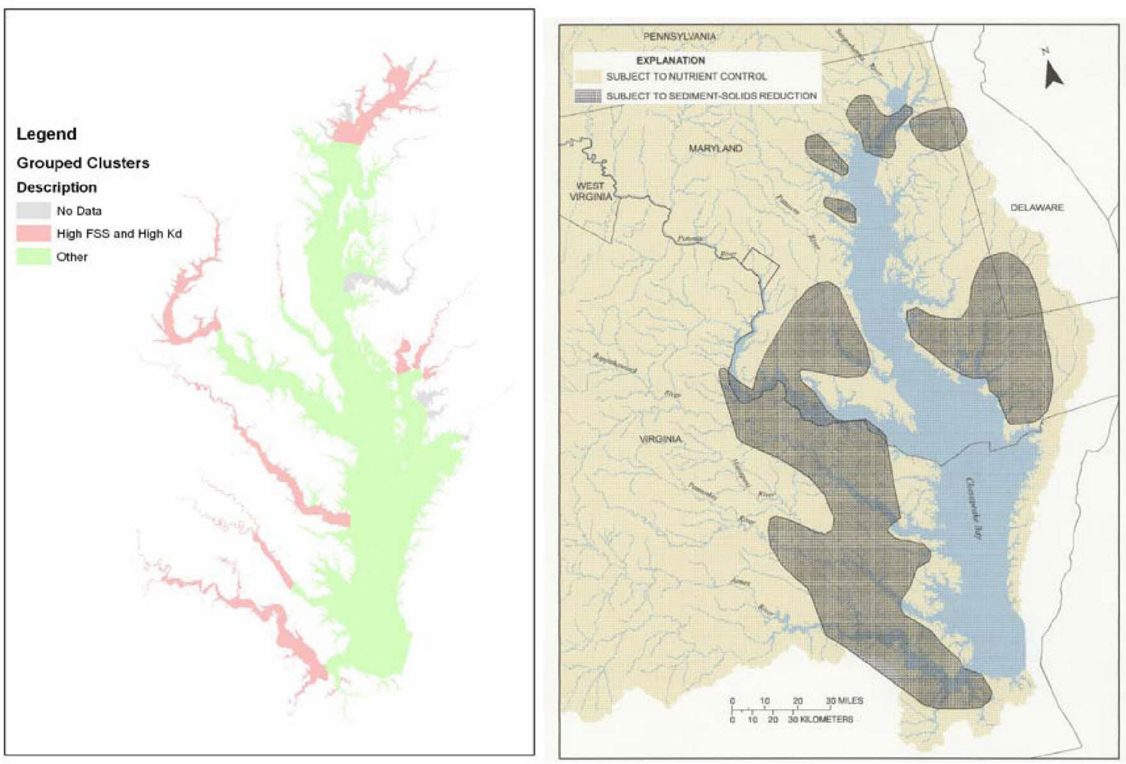

Figure 5-7. (Left) Cluster results show water quality segments exceeding the water clarity criteria with high percent fixed suspended solids (Currey and Wolf, 2007). (Right) Estuarine areas that benefit more from sediment controls (shaded area) than from nutrient controls (areas in yellow) in the watershed and tidal tributaries (Cerco et al, 2002).

6 Summary and Future Work

In this report we have attempted to lay the foundation needed to develop a sedimentshed. The Sediment Workgroup began (section two) with a review of the process applied in previous sediment allocations (USEPA, 2003c) and the uncertainty reported with respect to these allocations. Next (section three) the Sediment Workgroup reported the consensus decision on a definition of a sedimentshed as the area that contributes the sediment that directly influences water clarity in near-shore SAV growing areas. Further, in section three, we suggested that the first step when delineating a sedimentshed would require determining the appropriate scale of the SAV area where sediment sources are to be identified and provided considerations for defining this scale. In section four, we listed the second step in determining a sedimentshed as requiring an evaluation of the sediment sources in the nearshore area water column and their relative contribution and impact to water clarity. Section five provides an analysis that can be used to prioritize areas for sedimentshed development by identifying areas with high fixed suspended solids and high light attenuation, relative to the appropriate criteria.

While this report presents the components of and proposed plan for developing a sedimentshed, it does not provide results of a defined sedimentshed. The Sediment Workgroup's present opinion is that the delineation of a sedimentshed for a specific SAV region would require either monitoring data directed at identifying the source of the sediment (i.e. watershed, shore, resuspension, etc.) or a mechanistic, spatially and temporally varying model that accounts for the predominant physical processes governing Baywide sediment transport. Currently there is not a Baywide sediment source tracking monitoring program, however, there is a joint modeling effort by the Chesapeake Bay scientific community using the best science and information available to simulate the predominant sediment transport processes in the Bay watershed and the Bay tidal waters and the subsequent effect of suspended sediment on the SAV community. However this refined water quality model is not expected to be completed until the summer of 2007 (for testing runs only). As a result, it was determined that sedimentsheds probably could not be delineated until the model is completed, but the Workgroup has begun by setting the foundation for sedimentshed development.

The Sediment Workgroup is expecting the January 2007 STAC workshop to provide guidance of how to best proceed in supporting the 2010 Bay reallocation process. Three specific questions have been identified for discussion and are broadly defined as:

- What aspects of suspended sediment variability are most important for water clarity?
- Does sediment have the same impact on water clarity and SAV in all areas of the Bay? Which areas of the Bay would most likely benefit from local sediment reductions?
- What is the appropriate scale and once decided, what is the optimum approach to delineating sedimentsheds?

On January 30-31, 2007, the Science and Technology Advisory Committee hosted a Sedimentsheds Workshop which had three major objectives:

1. To provide a forum to share important insights from all invited experts on sediment, water clarity and submerged aquatic vegetation.
2. To review and comment on the Sediment Workgroup's draft report "Addressing Sediment and Its Relationship to Chesapeake Bay Water Clarity."
3. To provide the Sediment Workgroup with focused guidance in determining appropriate next steps for addressing sediment impacts to Bay water clarity as necessitated by the 2010 reevaluation.

Major conclusions and a summary of recommendations are outlined in the document: "STAC Workshop Final Report An Introduction to Sedimentsheds: Sediment and its Relationship to Water Clarity" available at www.chesapeakebay.net/pubs/STACFinalSedshedsReport.pdf

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8 Glossary

Bathymetry -- the topography, or contours, of the Bay bottom.

Fastland - land above tidal water, often called shoreline

Fetch – The distance across open water over which wind blows.

Geomorphology -- form and general configuration of the land of the area.

Nearshore – the shallow water close to the shoreline

SAV Grow Zones – See Shallow Water Bay Grass Designated Use (below)

Sediment – Is composed of loose particles of clay, silt and sand.

- Fine-grained sediment – refers to clay (less than 1/256-mm diameter) and silt (1/256 - 1/16mm diameter) sized fractions
- Coarse-grained sediment – refers to the sand (1/16-2mm diameter) and gravel (2-64mm diameter) sized fractions

The fine/coarse distinction is important because most coarse material is transported along the bottom of rivers and the Bay and has little effect on light penetration. In contract, fine-grained sediment commonly is found in suspension and variably blocks light penetration depending on it abundance, grain-size distribution, and degree of aggregation.

Shallow Water – Chesapeake Bay water less than 2 meters in depth

Shallow Water Bay Grass Designated Use -- This is a generally narrow ribbon of shallow water (less than 2 meter deep) along the tidal Bay shorelines where underwater grasses (SAV) can grow. It is one of five Chesapeake Bay tidal-water designated uses. This designed use is to protect underwater Bay grasses and the many fish and crab species that depend on the shallow-water habitat provided by grass beds. The Shallow Water Bay Grass Designated Use area is also known as SAV grow zones.

Water Clarity Criteria – State water quality regulations in Maryland, Virginia, Delaware and Washington, D.C. adopted in 2006 which require minimum light requirements through water in shallow (less than 2 meter depth) waters to facilitate submerged aquatic vegetation growth.